


Review

Which Type of Exercise Is More Beneficial for Cognitive Function? A Meta-Analysis of the Effects of Open-Skill Exercise versus Closed-Skill Exercise among Children, Adults, and Elderly Populations

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Abstract: A large number of studies have described a positive relationship between physical exercise and cognition. Physical exercise can be divided into closed-skill exercise (CSE) and open-skill exercise (OSE) based on the predictability of the performance environment. It remains unknown whether either of these types of exercise is more beneficial for cognitive function. Therefore, the purpose of this meta-analysis was to evaluate the effect of OSE versus CSE on cognition. Eligible studies included cross-sectional studies and intervention studies that had a clear definition of OSE and CSE, and these were used to compare the cognitive performance differences between the two classes of exercise. A total of 15 cross-sectional studies and 4 intervention studies were included in this meta-analysis. Among the cross-sectional studies, the overall effect size for OSE versus CSE was 0.304 (95% confidence interval (CI) (−0.097, 1.213); $p < 0.05$). Further subgroup analysis showed that the overall effect size for OSE versus CSE was 0.247 for inhibition and 0.360 for cognitive flexibility (both $p < 0.05$). In contrast, no significant differences between the two exercise modes were observed in the intervention studies. In particular, there were no significant differences in visuospatial attention or in processing speed between the two exercise modes. Taken together, these results suggest that OSE is superior to CSE, especially for executive function, according to the 15 cross-sectional studies examined. However, data from the intervention studies indicate that OSE is not superior. Therefore, additional well-designed, long-term intervention studies are needed to elucidate the potential efficacy of OSE in all populations.

Keywords: exercise modes; open-skill exercise; closed-skill exercise; cognitive function; executive function

1. Introduction

Physical exercise has the potential to improve several aspects of cognitive function over a lifetime [1], including attention [2], processing speed [3], working memory [4], and executive function [5]. Furthermore, this view is supported by many behavioral and imaging studies [6–9]. Specifically, physical exercise is conducive to the improvement of children’s academic performance [10], the increase of brain-derived neurotrophic factor concentration in adults [11], and the increase of brain volume in the elderly [12]. Cognitive function refers to the process of acquiring or applying knowledge, or the process of information processing [13], which is the most basic psychological process of humans.

Researchers have dissected cognitive function into more specific psychological abilities, such as perception, attention, working memory, decision-making, processing speed, planning, inhibition, cognitive flexibility, etc., to measure it simply and operationally [14–16]. Executive function produces coordinated, orderly, and targeted behaviors [14]. It has been demonstrated that executive function is a major component of exercise-induced cognitive improvement [17,18]. Three widely accepted subfunctions of executive function are inhibition, working memory, and cognitive flexibility [19].

Recent studies have demonstrated that exercise modes produce different cognitive benefits [20,21]. Consequently, the relationship between physical exercise and cognitive function has gained greater interest, with a goal of maximizing cognition as a result of physical exercise. Physical exercise is a branch of physical activity. It is defined as a planned, structured, and repetitive physical activity aimed at improving or maintaining one or more components of physical fitness [22]. Generally, physical exercise can be divided into two main modes. One mode is open-skill exercise (OSE), which requires players to react in dynamic, unpredictable, and externally-paced environments (e.g., basketball, football, tennis, and badminton) [20]. This exercise mode is accompanied by greater cognitive and executive loadings [23]. The second mode is closed-skill exercise (CSE), which involves a relatively consistent, controllable, and self-adjustable environment [8]. A well-designed, randomized controlled trial found that children participating in OSE (e.g., team games) outperformed children in CSE (e.g., aerobic exercise) in shifting performances [24]. Nevertheless, when Jacobson et al. selected young adults as subjects to explore the differences in inhibitory control between the two exercise modes, they found that young adults participating in CSE performed better [25]. Meanwhile, a cross-sectional study of older adults found no difference between the two exercise modes regarding visuospatial mental rotation tasks [3]. Many moderator variables may contribute to these vague results; for example, the age [26] and race [27] of participating subjects, the application of different task paradigms [28], and other variables may play a role. Thus, although many studies have compared the cognitive effects of these two exercise modes, there is no definitive evidence to prove which is better. It is hypothesized that the selection of an appropriate exercise mode can promote cognitive function in children and middle-aged individuals, and additionally may delay cognitive decline in the elderly. Given that physical activity has been shown to affect brain health and cognition in healthy people [29], and may delay cognitive decline in the elderly with dementia [30], finding more effective exercise modes to improve intelligence in children and delay cognitive aging in the elderly would be of great application value.

To date, no meta-analysis has been performed to compare the different effects of OSE and CSE on cognition. Therefore, we performed a comprehensive meta-analysis with no limitation on publication dates. A total of 19 studies were selected to examine three key issues: (1) the differences in overall cognitive function between OSE and CSE in all populations; (2) the differences in executive function between OSE and CSE in all populations, including inhibition, cognitive flexibility, visuospatial attention, and processing speed; and (3) to evaluate whether the results published to date apply to different populations.

2. Materials and Methods

The meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [31] to ensure its accuracy.

2.1. Search Strategy

A systematic search of five databases was conducted (Web of Science, EMBASE, Elsevier Science, PubMed, and PsycINFO) for literature published prior to September 2019. Two types of terms were used for the retrieval: “cognition” and “exercise mode.” Cognition-related terms included cognition, cognitive, working memory, attention, executive function, inhibitory control, and information processing. Exercise-mode-related terms included exercise type, exercise mode, open skill, and closed skill. Cognition- and exercise-mode-related terms were combined with “and” for the retrieval from the databases. In addition, references in the obtained articles were reviewed.

2.2. Selection Criteria

Studies that met the following inclusion criteria were considered eligible: (1) full-text studies written in English, (2) studies with an intervention or cross-sectional study design, (3) studies with CSE and OSE specifically defined and discussed as independent variables, and (4) studies that identified at least one cognition-related indicator as a dependent variable. After eliminating duplicate or irrelevant articles, the remaining articles were subjected to a full-text evaluation. Further screening was conducted according to the above four criteria, and articles meeting all criteria were included in the meta-analysis. An overview of the selection process and the numbers of included and excluded studies are provided in Figure 1.

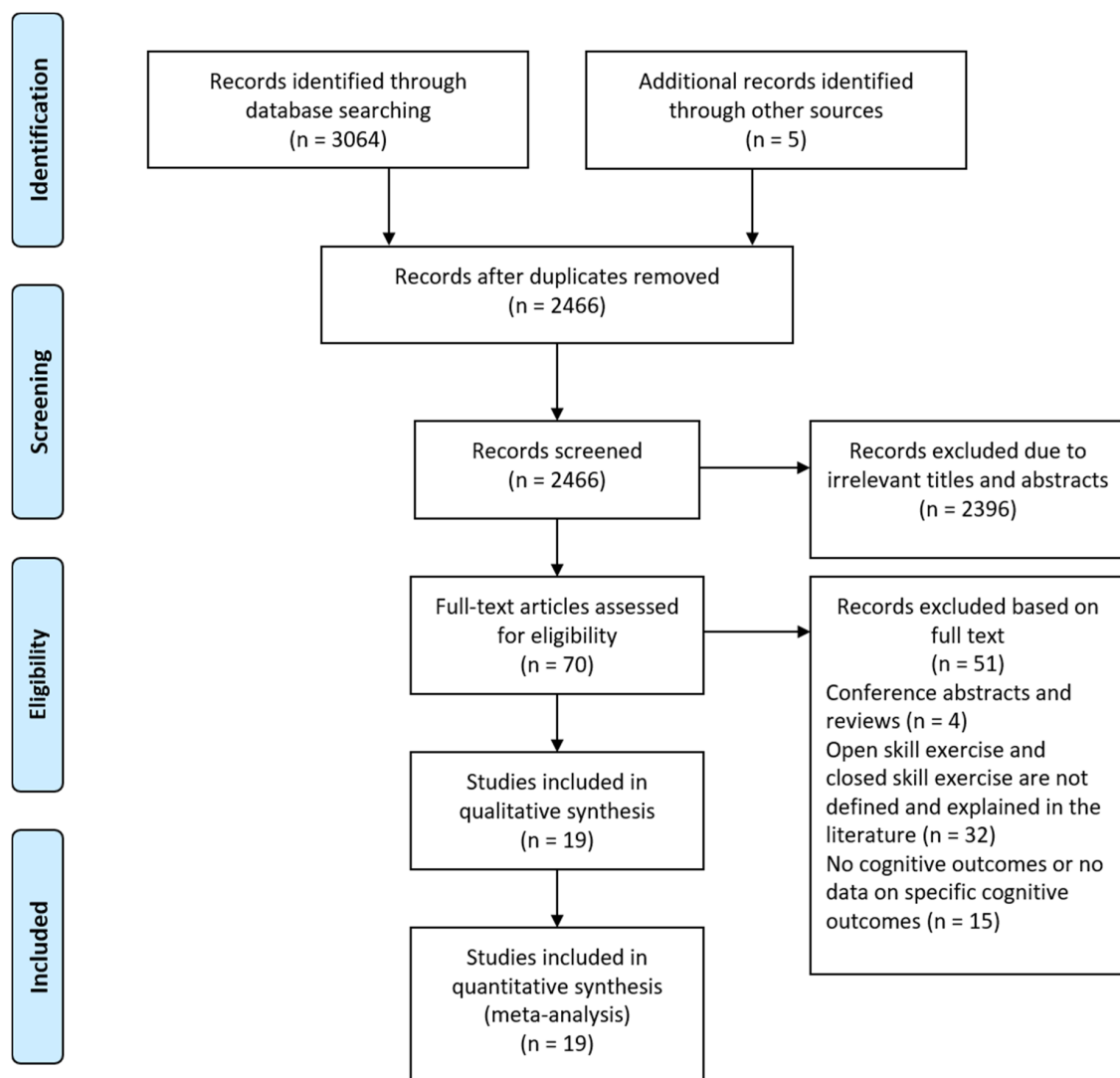


Figure 1. Flowchart of study selection.

2.3. Data Extraction and Analysis

The publication year, characteristics of the participants, intervention methods, exercise experience, and cognitive assessment tools were recorded for each cross-sectional and intervention study examined. The number of participants in the OSE and CSE groups, as well as the mean \pm standard deviation of the relevant data in the cognitive measurement tasks, were also extracted. For the intervention studies, the mean \pm standard deviation data at baseline and post-test were extracted from the cognitive measurement tasks. If the standard deviation data were not available, we converted the standard

error to a standard deviation [32], or calculated the standard deviation according to the upper and lower limits of the data (e.g., the 95% confidence interval (CI)). Comprehensive Meta-Analysis (CMA) version 3 (Bio-stat Inc., Englewood, NJ, USA) was used to summarize and analyze the data. For multi-term studies involving two or more cognitive tasks, each task was designated a type of cognitive function. Moreover, one task could include multiple subtasks. Over-quantities and inconsistencies of subtasks in evaluating different cognitive functions can lead to biased and unrepresentative results in a meta-analysis. Therefore, in each task, we screened the most representative results as a measure of cognitive function and ensured that each task had the same number of subtasks.

The specific cognitive functions involved in all of the observational studies we screened, including inhibition, cognitive flexibility, visuospatial attention, and processing speed, were classified. Each subfunction was further analyzed using CMA.

For the data analysis, based on the methodology used in other meta-analyses [33,34], we used the standard mean difference as the effect size of overall cognition in each study. The explanation of the effect size estimation is consistent with Cohen's guideline [35], in which 0.2 is a small effect, 0.5 is a medium effect, and 0.8 is a large effect. The significance of the p -value was set at $p < 0.05$. The statistical homogeneity (I^2) of the effect size was assessed using the Cochran's Q test. I^2 is usually used to indicate the proportion of heterogeneity; I^2 is considered low when it is less than 25%, 50%–75% is considered medium, and greater than or equal to 75% is considered high [36].

2.4. Risk of Bias Assessment

The generated results were analyzed for publication bias and a corresponding funnel plot was created. The asymmetry or incompleteness of a funnel chart means that publication bias may exist. It can only make a rough qualitative judgment on publication bias; therefore, it needs enough samples to make a judgment [37]. As such, only the 15 cross-sectional studies selected were analyzed for publication bias. The funnel chart produced (with the abscissa representing the effect quantity and the ordinate representing the standard error) showed a small sample bias. When the negative results were removed, the p -value remained significant ($p < 0.05$).

2.5. Study Quality Assessment

Considering the limited number of intervention studies available, only the 15 cross-sectional studies were examined. The quality of each cross-sectional study was rated by two independent reviewers (H.Z. and W.G.) by using a study quality assessment tool developed by Fuzeki et al. [38] and Engeroff et al. [39]. A total of 12 questions were presented, with 12 being the highest score possible. Two reviewers scored each study independently according to the detailed scoring criteria, and differences in scoring were settled by a third reviewer (B.W.).

3. Results

3.1. Included Studies

Keyword searches of five electronic databases (see Section 2.1 above) initially identified 3064 potential articles. An additional five records were identified by examining references in the most relevant studies. After eliminating duplicate or irrelevant articles, 70 studies were obtained. Two authors (H.Z. and F.Z.) jointly analyzed the selected articles. After excluding articles that did not meet our screening criteria, a total of 19 studies, including 15 cross-sectional studies [4,20,25,40–51] and 4 intervention studies [21,23,24,52] were selected for the analysis. The cross-sectional studies and intervention studies were analyzed separately. Characteristics of both sets of studies are summarized in Table 1; Table 2, respectively.

Table 1. Characteristics of the cross-sectional studies that were examined.

Study (First Author, Year)	Country	Sample Size OSE/CSE	Mean Age (y)	Measurement Tool	Cognitive Functions	OSE Activities	CSE Activities	Exercise Experience
Giglia, 2011	IT	12/10	23.38	Line-length judgment task	Visuospatial attention	Volleyball	Rowing	OSE: 3.4 ± 1.0 h/day CSE: 3.1 ± 0.5 h/day
Dai, 2013	CN	16/16	68.73	Task-switching paradigm	Cognitive flexibility	Table tennis or tennis	Jogging or swimming	Table tennis/tennis: 13.0 ± 5.7 y Jogging/swimming: 11.1 ± 4.5 y Irregular exercise: 0.7 ± 0.6 y
Wang, 2013a	CN	20/20	20.13	Stop-signal task	Inhibition	Tennis	Swimming	Tennis: 5.5 ± 2.8 y Swimming: 4.9 ± 1.7 y
Wang, 2013b	CN	14/14	20.4	Go/no-go task	Inhibition	Tennis	Swimming	Tennis: 3–11 y Swimming: 2.5–9 y
Huang, 2014	CN	20/20	69.43	Eriksen flanker task	Inhibition	Table tennis, tennis, badminton, etc.	Jogging, swimming, etc.	OSE group: 7.8 ± 1.1 y CSE group: 6.7 ± 2.4 y
Jacobson and Matthaeus, 2014	US	22/17	20.13	D-KEFS tower test, D-KEFS color–word interference test, coding test	Problem-solving, decision-making, inhibition, processing speed	Externally paced exercise	Self-paced exercise	Exercise group: 1×/week
Tsai and Wang, 2015	CN	21/22	65.11	Task-switching	Cognitive flexibility	Badminton or table tennis	Jogging or swimming	Exercise group: ≥30 min/session, ≥3×/wk, ≥2×/y
Guo, 2016	CN	36/38	67.06	VWMT, VSMT, VMTT	Visuospatial working memory	Table tennis	Jogging or swimming	Exercise group: ≥30 min/session, ≥3×/wk, ≥1×/y
Tsai, 2016	CN	20/20	65.53	Visuospatial attention paradigm	Visuospatial attention	Badminton or table tennis	Jogging or swimming	Exercise group: ≥30 min/session, ≥3×/wk, ≥2×/y

Table 1. Cont.

Study (First Author, Year)	Country	Sample Size OSE/CSE	Mean Age (y)	Measurement Tool	Cognitive Functions	OSE Activities	CSE Activities	Exercise Experience
Ballester, 2017	ES	20/20	11	Vigilance task session	Vigilance	Football	Track and field	Exercise group: 4 h/wk, $\geq 4 \times /y$
Chang, 2017	CN	15/14	21.32	Stroop task, WCST, Tower of London task	Inhibition, working memory, cognitive flexibility, planning	Martial arts training	Marathon running	Martial arts: 8.6 ± 2.3 y Marathon running: 7.8 ± 2.4 y Control group: 0.9 ± 1.7 y
Chueh, 2017	CN	9/9	20.6	NDMT	Visuospatial attention, visuospatial memory	Badminton or table tennis	Swimming, triathlon, or distance running	OSE group: 10.8 ± 2.2 y CSE group: 9.7 ± 3.2 y
Yu, 2017	CN	18/18	21.33	Task-switching paradigm, simple reaction task	Cognitive flexibility, processing speed	Badminton	Track and field	Badminton: 11.3 ± 2.7 y Track and field: 7.9 ± 1.6 y
Li et al., 2018	CN	23/24	68.88	SCWIT, task-switching paradigm	Inhibition, cognitive flexibility	Table tennis or tennis	Jogging or brisk walking	Exercise group: ≥ 30 min/session, $\geq 3 \times /wk$, $\geq 3 \times /month$
Ballester, 2019	ES	22/22	23.13	Psychomotor vigilance task, go/no-go task	Vigilance, inhibition	Football, basketball, volleyball, tennis, martial arts	Track and field, swimming, triathlon, cycling	EP athletes: 4.5 h/wk SP athletes: 5.5 h/wk Non-athletes: 0.7 h/wk

CN, China; CSE, closed-skill exercise; D-KEFS, Delis–Kaplan executive function system; ES, Spain; IT, Italy; NDMT, nondelayed and delayed matching-to-sample task; NVP, national-level volleyball player; NR, national-level rowers; OSE, open-skill exercise; RT, response time; RVP, regional-level volleyball player; SCWIT, Stroop color–word interference test; US, The United States; VMTT, visuospatial mental rotation task; VSMT, visuospatial short-term memory task; VWMT, visuospatial working memory task; WCST, Wisconsin card-sorting test.

Table 2. Characteristics of the intervention studies examined.

Study (First Author, Year)	Country	Sample Size OSE/CSE	Mean Age (y)	Measurement Tool	Cognitive Functions	OSE Activities	CSE Activities	Motion Cycle
Crova, 2014	IT	20/15	9.6	RNG task	Inhibition, working memory	Enhanced PE	Curricular PE	6 months
Schmidt, 2015	CH	26/28	11.33	N-back task, flanker task	Inhibition, cognitive flexibility, working memory	Team games	Aerobic exercise	6 weeks
Tsai, 2017	CN	22/21	66.28	Task-switching, n-back task	Cognitive flexibility, working memory	Table tennis	Bike riding or brisk walking/jogging	6 months
Hung, 2018	CN	20/20	23.15	Task-switching	cognitive flexibility	Badminton	Running	40 min

CH, Switzerland; CN, China; CSE, close-skilled exercise; IT, Italy; OSE, open-skilled exercise; PE, physical education; RNG, random number generation.

3.2. Comparison of Overall Cognitive Performance in Cross-Sectional Studies

The effects of OSE and CSE on overall cognitive function are summarized in Figure 2 (Raw data for all forest maps can be obtained in Supplementary Materials). The effect size for OSE versus CSE on overall cognition performance was 0.304 (95% CI $(-0.097, 1.213)$; $p < 0.05$). In addition, no significant heterogeneity was observed across the studies examined ($Q(14) = 16.207$; $p > 0.05$; $I^2 = 13.62\%$). In a funnel plot analysis, two of the included studies accounted for the observed asymmetry of the funnel plot (Funnel plots can be obtained from Supplementary Materials). One study [20] was outside the inverted cone and the other [44] was at the edge of the inverted cone. When these two studies were excluded, the significant results originally obtained were not affected, with an effect size of 0.192 (95% CI $[-0.097, 0.724]$; $p < 0.05$).

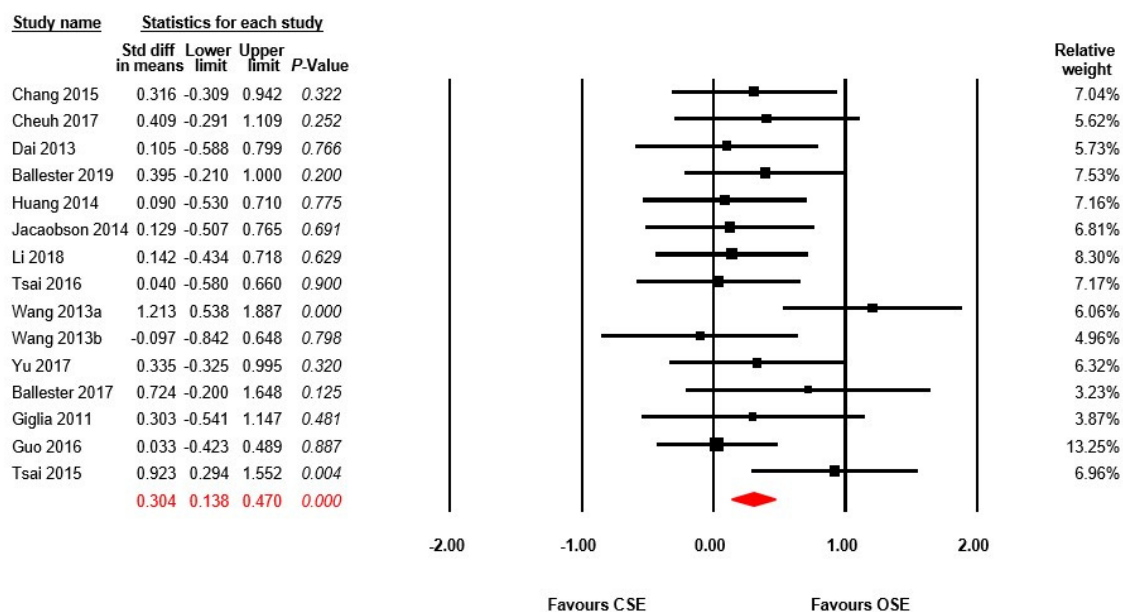


Figure 2. Forest plot for the efficacy of OSE compared to CSE in cross-sectional studies.

3.3. Specific Cognitive Performance

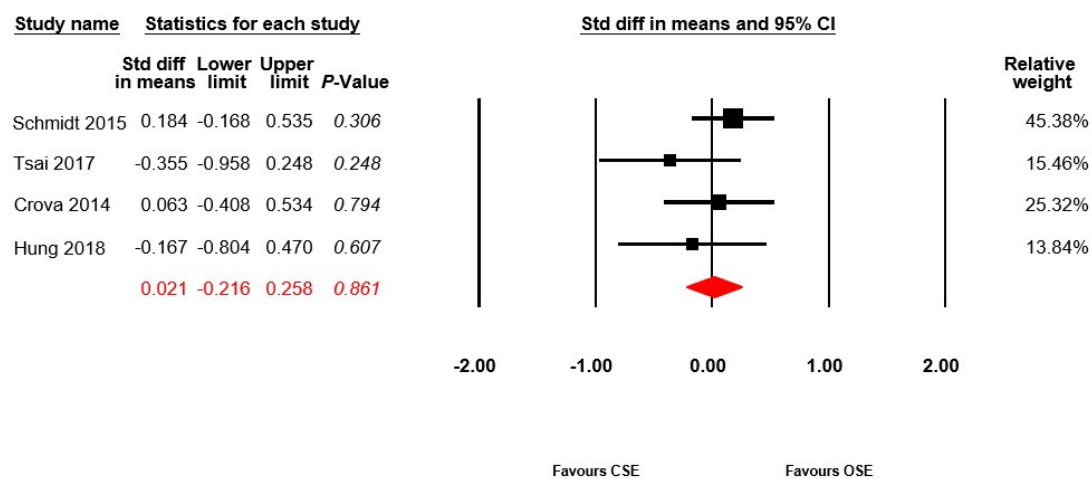
In each study, specific cognitive performance was selected as the evaluation index. Considering the small number of intervention studies selected, a subgroup analysis was conducted only for the 15 cross-sectional studies. Studies measuring the same type of cognitive ability were used to explore specific subfunctions of CSE and OSE to fully understand the ability of these two modes of exercise to promote cognitive performance. It is worth noting that each study adopted the same or similar paradigm for the measurement of specific subfunctions. The final results are presented in Table 3. Raw data for Tables 3 and 4 can be obtained in the Supplementary Materials. The overall effect size for OSE versus CSE on inhibition was 0.247 (95% CI $(-0.173, 1.213)$; $p = 0.042$). In addition, no significant heterogeneity was observed among the studies ($Q(6) = 10.529$; $p > 0.05$; $I^2 = 43.01\%$). Regarding cognitive flexibility, the combined effect size was 0.360 (95% CI $(0.036, 0.923)$; $p = 0.013$), and no significant heterogeneity was observed ($Q(4) = 5.382$; $p > 0.05$; $I^2 = 25.68\%$). Furthermore, no significant differences in visuospatial attention or processing speed were found between OSE and CSE.

Table 3. Conditions of specific performance.

Subfunction	Number of Studies	Effect Size	95% CI	p-Value
Inhibition	7	0.247	−0.173, 1.213	0.042
Cognitive flexibility	5	0.360	0.036, 0.923	0.013
Visuospatial attention	3	0.209	0.040, 0.359	0.314
Processing speed	2	0.103	0.098, 0.108	0.657

3.4. Comparison of Overall Cognitive Performance in Intervention Studies

A total of four intervention studies were analyzed, one of which adopted a within-subjects design [21]. Due to the small number of studies that met our criteria, we did not exclude the latter study. According to the forest plot shown in Figure 3, no significant difference in overall cognitive performance was observed between CSE and OSE.

**Figure 3.** Forest plot for the efficacy of OSE compared to CSE in intervention studies.

3.5. Moderator Analysis

The results of a moderator analysis of OSE versus CSE are summarized in Table 4. To analyze the influence of potential moderator variables on overall cognitive function, and considering that only a small number of intervention studies were available, we only analyzed the moderator variables of the 15 cross-sectional studies according to age group. These groups included children aged 5–16 years, young adults aged 17–35 years, and elderly aged >56 years. Our goal was to explore whether OSE and CSE influence the overall cognitive function of different age groups. Based on our selection criteria, we had one study of children, eight studies of young adults, and six studies of the elderly to evaluate. Consequently, we only compared differences for the younger and older adults. The effect size for OSE versus CSE on overall cognition in the young adults was 0.384 (95% CI (−0.097, 1.213); $p = 0.002$) (Table 4), and no significant heterogeneity was observed across these studies ($Q(7) = 8.129$, $p > 0.05$, $I^2 = 13.89\%$). Meanwhile, the effect size for OSE versus CSE on overall cognition in the older adults was 0.197 (95% CI (0.033, 0.923); $p = 0.105$) (Table 4). There was no significant heterogeneity observed between these studies either ($Q(5) = 6.077$, $p > 0.05$, $I^2 = 17.72\%$). Taken together, these results demonstrate that the cognitive benefits of OSE are greater for younger adults.

According to a previously described study quality assessment tool [38,39,53], each study was graded. Scores for the 15 cross-sectional studies ranged from 7 to 9. A score of 9 was considered to indicate high quality, 8 indicated moderate quality, and 7 indicated low quality (Detailed grading rules and scores for each article can be obtained in the Supplementary Materials). Differences in the effects of

OSE and CSE on cognitive function were found to be significant in both the high- and moderate-quality studies and were not significant in the low-quality articles.

Table 4. Moderator analysis for OSE versus CSE.

Moderator Variable (Categorical)	Level	Number of Studies	Effect Size	95% CI	<i>p</i> -Value
Age	Young adults	8	0.384	−0.097, 1.213	0.002
	Elderly	6	0.197	0.033, 0.923	0.105
Study quality	High	4	0.639	0.335, 1.213	0.000
	Moderate	9	0.235	0.033, 0.923	0.025
	Low	2	0.034	−0.097, 0.129	0.892

4. Discussion

To the best of our knowledge, this is the first meta-analysis of all age groups that compared the effects of CSE and OSE on cognitive performance based on results obtained from cross-sectional and intervention studies. Among the 15 cross-sectional studies examined, OSE was superior to CSE with a small effect regarding cognitive performance. Additional subgroup analyses further demonstrated that OSE led to positive effects on inhibition and cognitive flexibility compared to CSE. Meanwhile, visuospatial attention and processing speed did not exhibit significant differences between the two modes of exercise. Since inhibition and cognitive flexibility are both important subfunctions of executive function, these results provide preliminary support that OSE can achieve better executive function than CSE.

In contrast, among the four intervention studies examined, no significant differences were observed between OSE and CSE. Moreover, while the direction of the effect size was biased toward OSE, the associated *p*-value was not significant. Therefore, our research results only partially support the hypothesis that OSE is superior to CSE in terms of executive function.

4.1. Differences in Cognitive Function between OSE and CSE

Consistent with the findings of a recent systematic review [53], we found OSE to be more effective at improving cognitive performance than CSE. Furthermore, when we refined cognitive performance, OSE produced better inhibition and cognitive flexibility than CSE. In two previous studies [43,50], event-related potential was used to compare OSE and CSE, and the former exhibited a better electrophysiological performance. These results are also consistent with the present findings.

Regarding visuospatial attention, previous studies have produced conflicting views. For example, when Giglia et al. focused on the lateralization of athletes' visuospatial attention, no significant difference in visuospatial attention was observed between the CSE and control groups [40]. Moreover, the performance of both groups was worse than that for OSE, suggesting that a stable sports environment may not effectively train individuals to distract their visuospatial attention. In contrast, another study conducted by Chueh et al. showed no difference in visuospatial attention between OSE and CSE [47]. We are more inclined to support the former result based on our understanding of the two exercise modes. It should be noted that data for the present meta-analysis exhibited a relatively large effect size that was biased toward OSE. However, the results were not significant. There are two possible reasons for the latter observation. One, with only three studies included in our analysis, our results are based on a very small sample size. Second, the subjects evaluated for visuospatial attention were mostly young adults. Thus, the absence of children and the elderly as study subjects may also have contributed to our insignificant results. The results of the present study also confirmed that no significant difference exists between the two exercise modes regarding the performance of processing-speed-related tasks [48].

To further enrich and support the findings of the cross-sectional studies examined, we analyzed four intervention studies. The main reason for incorporating the intervention studies was to facilitate causal inference. Of the four articles we examined, two [24,52] provided support that OSE is better

for cognitive promotion, one study showed that OSE and CSE have unique advantages for specific cognitive subfunctions [23], and the final study showed no difference between the two exercise modes at the behavioral level [21]. The results of the present meta-analysis indicate that there was no significant difference in the promotion of cognitive ability between OSE and CSE. Possible reasons for this result are that there were not many intervention studies available that have investigated the effects of these two modes of exercise on cognition, and only one of the four papers we examined could cause a large error in the meta-analysis. Therefore, in future studies, it will be important to include a greater number of intervention studies to ensure that reliable results are obtained. Second, the cognitive improvement from exercise appears to be related to intervention duration. This finding is supported by a recent systematic review in which it is demonstrated that only long-term exercise plays a positive role in brain function and structure [18]. For our meta-analysis, we included three long-term exercise studies [23,24,52], as well as a short-term exercise study [21]. Thus, a potential cause of our inconclusive results may be that we included all four studies for analysis. However, due to the limited number of articles included, it is not feasible to judge the correctness of this conjecture based on the moderate analysis grouped by intervention duration. Thus, additional studies are needed. It is worth mentioning that a recently published study shows that CSE provides more obvious advantages for retrospective memory than OSE after acute exercise [54]. A possible reason for the inconsistency may be mainly due to the different experimental paradigms. In the future, more intervention studies are needed to further reveal the different effects between the two exercise modes.

In summary, the results of this meta-analysis show that OSE was more effective than CSE in promoting the development of cognitive function. Moreover, this difference was reflected in higher cognitive processes, namely executive function.

4.2. Potential Mechanism for OSE's Superiority to CSE

In the present meta-analysis, OSE was found to have a greater benefit for cognitive function than CSE. However, the effect differed according to specific cognitive domains. In particular, OSE was more likely to promote inhibition and cognitive flexibility. We hypothesize that this result was due to participants' need to mobilize more cognitive resources in self-control and transformation to adapt to changes in the external information and the multisensory environments of OSE [55]. In contrast, CSE involves a relatively predictable and stable environment. Thus, fewer cognitive resources need to be mobilized during this mode of exercise. Inhibition and cognitive flexibility are important components of executive function. In OSE, this high-level cognitive process could be improved. In terms of processing speed, since the measurements of processing speed are based on relatively simple tasks, the cognitive resources required for mobilization are very limited. Therefore, no significant differences between OSE and CSE were observed when considering tasks requiring a low cognitive level [48,56].

Regarding visuospatial attention, our meta-analysis did not identify any differences between the two exercise modes. Exercise in a complex environment has been shown to increase the cortical thickness, neurogenesis, and heighten neurotransmission [57,58]. Moreover, a prior study found that prefrontal cortex activation is much greater in children than in adults [59]. In addition, the prefrontal cortex plays an important role in resisting interference and maintaining targets. Thus, the effects of different exercise modes on visuospatial attention vary in different age groups. To date, very few studies have included children and the elderly in the evaluations of modes of exercise. Consequently, a lack of comprehensive coverage of the characteristics of these subjects may account for the insignificant results we obtained. Moreover, the latter partly explains current inconsistencies among views of the two exercise modes regarding visuospatial attention.

From the perspective of educational applications, the current evidence indicates that OSE was more beneficial to the cognitive development of normal people, and these findings will be helpful to the replanning and arrangement of physical education for education decision-makers. In terms of clinical application, physical exercise has also been proved to be an effective means to improve mild

cognitive impairment and dementia [60]. Therefore, we speculate that the unique advantage of OSE in cognitive ability may also exist in special groups.

Our results suggest that, compared with CSE, OSE had more advantages in improving cognitive function at the behavioral level. It provides some implications for people's choice of exercise modes. This existing finding could be further extended to the level of brain mechanisms in the future.

4.3. Strengths and Limitations

A major advantage of our meta-analysis is that it provides an up-to-date summary of differences in the effects of CSE and OSE on cognitive performance without limitations regarding the experimental design methods, age of subjects, and publication date. However, the conclusions of this meta-analysis should be considered regarding the following limitations. First, only 4 out of the 19 studies examined were intervention studies. Thus, our meta-analysis of the intervention studies was not sufficiently reliable, and the conclusions can only provide some references and suggestions for future research. Moreover, future studies need to cautiously consider causal inference. Second, the cross-sectional studies examined did not provide specifics regarding exercise time, frequency, and specific task performance for each of the participating genders. Therefore, the number of regulatory variables was not sufficient for further analysis, and this was not conducive for explorations of sources of heterogeneity. Third, while our moderator analysis indicated that OSE provided greater cognitive benefits to young adults, there have only been a few studies that investigated children participating in OSE. Therefore, it remains for future studies to confirm whether OSE is beneficial for children.

Finally, we only used behavioral data to determine differences in cognitive performance between the two exercise modes. In future studies, it will be important to employ functional magnetic resonance imaging (fMRI) technology to explore functional and structural changes in the brain that affect cognition as a result of the two exercise modes. Key considerations will be which exercise mode is more helpful in promoting and updating current inference and which neural mechanism(s) underlie the changes observed. Additionally, our search strategy was limited to full-text studies published in English. Future studies should include all relevant literature, independent of language, to have a complete dataset that is not biased according to language.

5. Conclusions

Compared with CSE, OSE improved cognitive function more effectively, regardless of baseline age. The benefits of OSE were especially apparent in inhibition and cognitive flexibility, and these should potentially promote better executive function. In addition, the results of the moderator analysis showed that the cognitive benefits of OSE were greater in young people. However, it is important to interpret the present results with caution due to the limited number of studies available. It is recommended that long-term intervention studies, as well as the use of fMRI, should be used to uncover the underlying brain mechanisms by which OSE affects cognitive function.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3417/10/8/2737/s1>, The original data of Figures 2 and 3 and Tables 3 and 4 of the main text can be obtained in the supplementary materials.

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References

- Hillman, C.H.; Erickson, K.I.; Kramer, A.F. Be smart, exercise your heart: Exercise effects on brain and cognition. *Nat. Rev. Neurosci.* **2008**, *9*, 58–65. [[CrossRef](#)] [[PubMed](#)]
- Fernandes, M.; de Sousa, A.; Medeiros, A.R.; Del Rosso, S.; Stults-Kolehmainen, M.; Boullosa, D.A. The influence of exercise and physical fitness status on attention: A systematic review. *Int. Rev. Sport Exerc. Psychol.* **2019**, *12*, 202–234. [[CrossRef](#)]
- Smith, P.J.; Blumenthal, J.A.; Hoffman, B.M.; Cooper, H.; Strauman, T.A.; Welsh-Bohmer, K.; Browndyke, J.N.; Sherwood, A. Aerobic exercise and neurocognitive performance: A meta-analytic review of randomized controlled trials. *Psychosom. Med.* **2010**, *72*, 239. [[CrossRef](#)] [[PubMed](#)]
- Guo, W.; Wang, B.; Lu, Y.; Zhu, Q.; Shi, Z.; Ren, J. The relationship between different exercise modes and visuospatial working memory in older adults: A cross-sectional study. *PeerJ* **2016**, *4*, e2254. [[CrossRef](#)] [[PubMed](#)]
- Chen, A.G.; Yan, J.; Yin, H.C.; Pan, C.Y.; Chang, Y.K. Effects of acute aerobic exercise on multiple aspects of executive function in preadolescent children. *Psychol. Sport Exerc.* **2014**, *15*, 627–636. [[CrossRef](#)]
- Davis, C.L.; Tomporowski, P.D.; McDowell, J.E.; Austin, B.P.; Miller, P.H.; Yanasak, N.E.; Allison, J.D. Exercise improves executive function and achievement and alters brain activation in overweight children: A randomized, controlled trial. *Health Psychol.* **2011**, *30*, 91. [[CrossRef](#)]
- Yanagisawa, H.; Dan, I.; Tsuzuki, D.; Kato, M.; Okamoto, M.; Kyutoku, Y.; Soya, H. Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves cognitive performance with Stroop test. *Neuroimage* **2010**, *50*, 1702–1710. [[CrossRef](#)]
- Voss, M.W.; Kramer, A.F.; Basak, C.; Prakash, R.S.; Roberts, B. Are expert athletes ‘expert’ in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Appl. Cogn. Psychol.* **2010**, *24*, 812–826. [[CrossRef](#)]
- Sexton, C.E.; Betts, J.F.; Demnitz, N.; Dawes, H.; Ebmeier, K.P.; Johansen-Berg, H. A systematic review of MRI studies examining the relationship between physical fitness and activity and the white matter of the ageing brain. *Neuroimage* **2016**, *131*, 81–90. [[CrossRef](#)]
- Sibley, B.A.; Etnier, J.L. The relationship between physical activity and cognition in children: A meta-analysis. *Pediatric Exerc. Sci.* **2003**, *15*, 243–256. [[CrossRef](#)]
- Hwang, J.; Brothers, R.M.; Castelli, D.M.; Glowacki, E.M.; Chen, Y.T.; Salinas, M.M.; Kim, J.; Jung, Y.; Calvert, H.G. Acute high-intensity exercise-induced cognitive enhancement and brain-derived neurotrophic factor in young, healthy adults. *Neurosci. Lett.* **2016**, *630*, 247–253. [[CrossRef](#)] [[PubMed](#)]
- Colcombe, S.J.; Erickson, K.I.; Raz, N.; Webb, A.G.; Cohen, N.J.; McAuley, E.; Kramer, A.F. Aerobic fitness reduces brain tissue loss in aging humans. *J. Gerontol. Ser. A Biol. Sci. Med. Sci.* **2003**, *58*, M176–M180. [[CrossRef](#)] [[PubMed](#)]
- Hunt, D. Understanding Literacy and Cognition. In *Cognition and Learning*; Springer: Boston, MA, USA, 1989; pp. 73–84.
- Funahashi, S. Neuronal mechanisms of executive control by the prefrontal cortex. *Neurosci. Res.* **2001**, *39*, 147–165. [[CrossRef](#)]
- Diamond, A. The early development of executive functions. *Lifesp. Cogn. Mech. Chang.* **2006**, *210*, 70–95. [[CrossRef](#)]
- Strauss, E.; Sherman, E.M.S.; Spreen, O. *A Compendium of Neuropsychological Tests: Administration, Norms, and Commentary*; Oxford University Press: New York, NY, USA, 2006.
- Hall, C.D.; Smith, A.L.; Keele, S.W. The impact of aerobic activity on cognitive function in older adults: A new synthesis based on the concept of executive control. *Eur. J. Cogn. Psychol.* **2001**, *13*, 279–300. [[CrossRef](#)]
- Guiney, H.; Machado, L. Benefits of regular aerobic exercise for executive functioning in healthy populations. *Psychon. Bull. Rev.* **2013**, *20*, 73–86. [[CrossRef](#)]
- Miyake, A.; Friedman, N.P.; Emerson, M.J.; Witzki, A.H.; Howerter, A.; Wager, T.D. The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cogn. Psychol.* **2000**, *41*, 49–100. [[CrossRef](#)]
- Wang, C.H.; Chang, C.C.; Liang, Y.M.; Shih, C.M.; Chiu, W.S.; Tseng, P.; Hung, D.L.; Tzeng, O.J.L.; Muggleton, N.G.; Juan, C.H. Open vs. closed skill sports and the modulation of inhibitory control. *PLoS ONE* **2013**, *8*. [[CrossRef](#)]

21. Hung, C.L.; Tseng, J.W.; Chao, H.H.; Hung, T.M.; Wang, H.S. Effect of acute exercise mode on serum brain-derived neurotrophic factor (BDNF) and task switching performance. *J. Clin. Med.* **2018**, *7*, 301. [\[CrossRef\]](#)
22. Caspersen, C.J.; Powell, K.E.; Christenson, G.M. Physical activity, exercise, and physical fitness: Definitions and distinctions for health-related research. *Public Health Rep.* **1985**, *100*, 126–131. [\[CrossRef\]](#)
23. Tsai, C.L.; Pan, C.Y.; Chen, F.C.; Tseng, Y.T. Open-and closed-skill exercise interventions produce different neurocognitive effects on executive functions in the elderly: A 6-month randomized, controlled trial. *Front. Aging Neurosci.* **2017**, *9*, 294. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Schmidt, M.; Jäger, K.; Egger, F.; Roebbers, C.M.; Conzelmann, A. Cognitively engaging chronic physical activity, but not aerobic exercise, affects executive functions in primary school children: A group-randomized controlled trial. *J. Sport Exerc. Psychol.* **2015**, *37*, 575–591. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Jacobson, J.; Matthaeus, L. Athletics and executive functioning: How athletic participation and sport type correlate with cognitive performance. *Psychol. Sport Exerc.* **2014**, *15*, 521–527. [\[CrossRef\]](#)
26. Peng, H.; Gao, Y.; Mao, X. The roles of sensory function and cognitive load in age differences in inhibition: Evidence from the Stroop task. *Psychol. Aging* **2017**, *32*, 42. [\[CrossRef\]](#)
27. Zsembik, B.A.; Peek, M.K. Race differences in cognitive functioning among older adults. *J. Gerontol. Ser. B Psychol. Sci. Soc. Sci.* **2001**, *56*, S266–S274. [\[CrossRef\]](#)
28. Korz, V.; Frey, J.U. Emotional and cognitive reinforcement of rat hippocampal long-term potentiation by different learning paradigms. *Neuron Glia Biol.* **2004**, *1*, 253–261. [\[CrossRef\]](#)
29. Hillman, C.H.; Kamijo, K.; Scudder, M. A review of chronic and acute physical activity participation on neuroelectric measures of brain health and cognition during childhood. *Prev. Med.* **2011**, *52*, S21–S28. [\[CrossRef\]](#)
30. Jia, R.; Liang, J.; Xu, Y.; Wang, Y.Q. Effects of physical activity and exercise on the cognitive function of patients with Alzheimer disease: A meta-analysis. *BMC Geriatr.* **2019**, *19*, 181. [\[CrossRef\]](#)
31. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; Altman, D.; Antes, G.; Atkins, D.; Barbour, V.; Barrowman, N.; Berlin, J.A.; et al. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *BMJ* **2009**, *339*, b2535. [\[CrossRef\]](#)
32. Streiner, D.L. Maintaining standards: Differences between the standard deviation and standard error, and when to use each. *Can. J. Psychiatry* **1996**, *41*, 498–502. [\[CrossRef\]](#)
33. Lampit, A.; Hallock, H.; Valenzuela, M. Computerized cognitive training in cognitively healthy older adults: A systematic review and meta-analysis of effect modifiers. *PLoS Med.* **2014**, *11*. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Zhu, X.; Yin, S.; Lang, M.; He, R.; Li, J. The more the better? A meta-analysis on effects of combined cognitive and physical intervention on cognition in healthy older adults. *Ageing Res. Rev.* **2016**, *31*, 67–79. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Cohen, J. A power primer. *Psychol. Bull.* **1992**, *112*, 155. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Higgins, J.P.T.; Thompson, S.G.; Deeks, J.J.; Altman, D.G. Measuring inconsistency in meta-analyses. *BMJ* **2003**, *327*, 557–560. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Sterne, J.A.C.; Harbord, R.M. Funnel plots in meta-analysis. *Stata J.* **2004**, *4*, 127–141. [\[CrossRef\]](#)
38. Fuezeki, E.; Engeroff, T.; Banzer, W. Health benefits of light-intensity physical activity: A systematic review of accelerometer data of the National Health and Nutrition Examination Survey (NHANES). *Sports Med.* **2017**, *47*, 1769–1793. [\[CrossRef\]](#)
39. Engeroff, T.; Ingmann, T.; Banzer, W. Physical activity throughout the adult life span and domain-specific cognitive function in old age: A systematic review of cross-sectional and longitudinal data. *Sports Med.* **2018**, *48*, 1405–1436. [\[CrossRef\]](#)
40. Giglia, G.; Brighina, F.; Zangla, D.; Bianco, A.; Chiavetta, E.; Palma, A.; Fierro, B. Visuospatial attention lateralization in volleyball players and in rowers. *Percept. Mot. Sk.* **2011**, *112*, 915–925. [\[CrossRef\]](#)
41. Dai, C.T.; Chang, Y.K.; Huang, C.J.; Hung, T.M. Exercise mode and executive function in older adults: An ERP study of task-switching. *Brain Cogn.* **2013**, *83*, 153–162. [\[CrossRef\]](#)
42. Wang, C.H.; Chang, C.C.; Liang, Y.M.; Shih, C.M.; Muggleton, N.G.; Juan, C.H. Temporal preparation in athletes: A comparison of tennis players and swimmers with sedentary controls. *J. Mot. Behav.* **2013**, *45*, 55–63. [\[CrossRef\]](#)
43. Huang, C.J.; Lin, P.C.; Hung, C.L.; Chang, Y.K.; Hung, T.M. Type of physical exercise and inhibitory function in older adults: An event-related potential study. *Psychol. Sport Exerc.* **2014**, *15*, 205–211. [\[CrossRef\]](#)

44. Tsai, C.L.; Wang, W.L. Exercise-mode-related changes in task-switching performance in the elderly. *Front. Behav. Neurosci.* **2015**, *9*, 56. [[CrossRef](#)] [[PubMed](#)]
45. Tsai, C.L.; Wang, C.H.; Pan, C.Y.; Chen, F.C.; Huang, S.Y.; Tseng, Y.T. The effects of different exercise types on visuospatial attention in the elderly. *Psychol. Sport Exerc.* **2016**, *26*, 130–138. [[CrossRef](#)]
46. Chang, E.C.H.; Chu, C.H.; Karageorghis, C.I.; Wang, C.C.; Tsai, J.H.C.; Wang, Y.S.; Chang, Y.K. Relationship between mode of sport training and general cognitive performance. *J. Sport Health Sci.* **2017**, *6*, 89–95. [[CrossRef](#)] [[PubMed](#)]
47. Chueh, T.Y.; Huang, C.J.; Hsieh, S.S.; Chen, K.F.; Chang, Y.K.; Hung, T.M. Sports training enhances visuo-spatial cognition regardless of open-closed typology. *PeerJ* **2017**, *5*, e3336. [[CrossRef](#)]
48. Yu, Q.; Chan, C.C.H.; Chau, B.; Fu, A.S. Motor skill experience modulates executive control for task switching. *Acta Psychol.* **2017**, *180*, 88–97. [[CrossRef](#)]
49. Ballester, R.; Huertas, F.; Molina, E.; Sanabria, D. Sport participation and vigilance in children: Influence of different sport expertise. *J. Sport Health Sci.* **2018**, *7*, 497–504. [[CrossRef](#)]
50. Li, D.; Huang, C.J.; Liu, S.C.; Chang, K.H.; Hung, T.M. Exercise type relates to inhibitory and error processing functions in older adults. *Aging Neuropsychol. Cogn.* **2019**, *26*, 865–881. [[CrossRef](#)]
51. Ballester, R.; Huertas, F.; Pablos-Abella, C.; Llorens, F.; Pesce, C. Chronic participation in externally paced, but not self-paced sports is associated with the modulation of domain-general cognition. *Eur. J. Sport Sci.* **2019**, *19*, 1110–1119. [[CrossRef](#)]
52. Crova, C.; Struzzolino, I.; Marchetti, R.; Masci, I.; Vannozzi, G.; Forte, R.; Pesce, C. Cognitively challenging physical activity benefits executive function in overweight children. *J. Sports Sci.* **2014**, *32*, 201–211. [[CrossRef](#)]
53. Gu, Q.; Zou, L.; Loprinzi, P.D.; Quan, M.; Huang, T. Effects of open versus closed skill exercise on cognitive function: A systematic review. *Front. Psychol.* **2019**, *10*, 1707. [[CrossRef](#)] [[PubMed](#)]
54. Cantrelle, J.; Burnett, G.; Loprinzi, P.D. Acute exercise on memory function: Open *vs.* closed skilled exercise. *Health Promot. Perspect.* **2020**, *10*, 123–128. [[CrossRef](#)]
55. Di Russo, F.; Bultrini, A.; Brunelli, S.; Delussu, A.S.; Polidori, L.; Taddei, F.; Traballes, M.; Spinelli, D. Benefits of sports participation for executive function in disabled athletes. *J. Neurotrauma* **2010**, *27*, 2309–2319. [[CrossRef](#)] [[PubMed](#)]
56. Nakamoto, H.; Mori, S. Effects of stimulus–response compatibility in mediating expert performance in baseball players. *Brain Res.* **2008**, *1189*, 179–188. [[CrossRef](#)] [[PubMed](#)]
57. Artola, A.; Von Frijtag, J.C.; Fermont, P.C.J.; Gispen, W.H.; Schrama, L.H.; Kamal, A.; Spruijt, B.M. Long-lasting modulation of the induction of LTD and LTP in rat hippocampal CA1 by behavioural stress and environmental enrichment. *Eur. J. Neurosci.* **2006**, *23*, 261–272. [[CrossRef](#)]
58. Nithianantharajah, J.; Hannan, A.J. Enriched environments, experience-dependent plasticity and disorders of the nervous system. *Nat. Rev. Neurosci.* **2006**, *7*, 697–709. [[CrossRef](#)]
59. Casey, B.J.; Giedd, J.N.; Thomas, K.M. Structural and functional brain development and its relation to cognitive development. *Biol. Psychol.* **2000**, *54*, 241–257. [[CrossRef](#)]
60. Prakash, R.S.; Voss, M.W.; Erickson, K.I.; Kramer, A.F. Physical activity and cognitive vitality. *Annu. Rev. Psychol.* **2015**, *66*, 769–797. [[CrossRef](#)]

